Influence of solution chemistry on the inactivation of particle-associated viruses by UV irradiation

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Abstract

MS2 inactivation by UV irradiance was investigated with the focus on how the disinfection efficacy is influenced by bacteriophage MS2 aggregation and adsorption to particles in solutions with different compositions. Kaolinite and *Microcystis aeruginosa* were used as model inorganic and organic particles, respectively. In the absence of model particles, MS2 aggregates formed in either 1 mM NaCl at pH=3 or 50-200 mM ionic strength CaCl_2 solutions at pH=7 led to a decrease in the MS2 inactivation efficacy because the virions located inside the aggregate were protected from the UV irradiation. In the presence of kaolinite and *Microcystis aeruginosa*, MS2 adsorbed onto the particles in either 1 mM NaCl at pH=3 or 50-200 mM CaCl_2 solutions at pH=7. In contrast to MS2 aggregates formed without the presence of particles, more MS2 virions adsorbed on these particles were exposed to UV irradiation to allow an increase in MS2 inactivation. In either 1 mM NaCl at pH from 4 to 8 or 2-200 mM NaCl solutions at pH=7, the absence of MS2 aggregation and adsorption onto the model particles explained why MS2 inactivation was not influenced by pH, ionic strength, and the presence of model particles in these conditions. The influence of virus adsorption and aggregation on the UV disinfection efficiency found in this research suggests the necessity of accounting for particles and cation composition in virus inactivation for drinking water.

Keywords: UV disinfection, MS2, kaolinite, *Microcystis aeruginosa*, particle-association.

1. Introduction

Virus disinfection can be a serious challenge in providing safe drinking water. However, not enough attention has been paid to virus disinfection compared to bacteria disinfection because of the lack of systematic monitoring of viruses in most countries. Many human enteric viruses, like rotavirus, norovirus, and enterovirus, could cause outbreaks of infectious diseases [1]. Severe diarrhea for children under the age of 5 due to rotavirus infection caused up to 591,000 deaths/year in 2000 and 233,000 deaths/year in 2013 [2]. Hepatitis A and hepatitis E viral infections could be related to untreated or improperly treated drinking water [3]. Hepatitis E infection is particularly severe for pregnant women, with the mortality rate as high as 25% [4]. Norovirus transmits through the fecal-oral route and causes acute gastroenteritis among people of all ages [5]. To prevent the transmission of human pathogenic viruses, special attention needs to be paid to virus disinfection in water treatment.

Most physical processes in water treatment, including coagulation, sedimentation, and granular filtration, are not capable of sufficiently removing viruses because of the nanometer size of the virions [6] and the unfavorable virus aggregation or adsorption to sand surfaces [7-9]. For these reasons, the control of virus contamination in drinking water relies on disinfection processes. Chlorination, ozonation, and UV irradiation are widely accepted disinfection processes. Compared to chlorination, UV irradiation has the advantage of producing less toxic disinfection byproducts (DBP) [10]. Though ozone is a strong disinfectant [11], the high cost of operation and maintenance and the production of toxic bromate DBP are of concern [12, 13]. UV disinfection has some advantages over chlorination and ozonation, because of the lack of toxic DBP formation and the relatively low cost, respectively [14].

In this study, we investigated how virus disinfection by UV irradiation is influenced

by virus aggregation and adsorption to suspended particles. While in physical treatment processes including coagulation and filtration, the occurrence of virus aggregation or adsorption to suspended particles has been reported to increase the virus removal [15-17], it is not understood yet how the virus aggregation or adsorption to suspended particles would influence the virus disinfection by UV irradiation. Bacteria disinfection efficacy by UV irradiation has been shown to decrease when bacteria cells adsorbed to suspended particles [18]. However, this observation may not be applicable for virus disinfection due to the different structures of virus and bacteria.

We hypothesize that virus aggregation and adsorption influence virus disinfection efficacy by UV irradiation due to the decrease in UV exposure. Algae bloom has become one of most serious water problem in south China [19, 20]. Because algal particles are difficult to neutralize and destabilize under the conditions relevant for drinking water treatment in south China [21], the removal of algae is usually not satisfactory, allowing them to be present in the disinfection reactor [22]. Besides algae, inorganic particles could also be present, especially if the water source is turbid surface water. These inorganic particles could influence the virus disinfection efficacy by UV irradiation. For these reasons, the influence of *Microcystis aeruginosa*, a model algae, and kaolinite, a model inorganic particle, on virus disinfection efficacy by UV irradiation is investigated in this study. Bacteriophage MS2 is used as the surrogate for enteric viruses for their similarities in size and structure [23]. MS2 aggregation and adsorption to suspended particles are studied under relevant environmental factors including pH conditions, concentrations of suspended particles, and cation concentrations [7, 24]. By understanding the influence of water source chemical composition on the relationship between the disinfection efficacy and virus

adsorption/aggregation, virus disinfection by UV irradiation can be better controlled for safe water treatment.

2. Materials and Methods

2.1 Material and Solution Preparation

Analytical grade NaOH, HCl, and NaHCO₃ were purchased from Sinopharm Chemical Reagent CO., Ltd (Shanghai, China). Kaolinite was purchased from Sigma-Aldrich (United States). Mediums for MS2 propagation (solid, semisolid, and liquid) were purchased from Qingdao Hope Bio-Technology Co., Ltd (Qingdao, China). MS2 (ATCC 15597-B1) and its *E. coli* host (ATCC 15597) were purchased from American Type Culture Collection (ATCC, Manassas, USA). *Microcystis aeruginosa* was supplied by the Institute of Hydrobiology, Chinese Academy of Sciences (Wuhan, China).

2.2 MS2 Propagation and Purification

The method for MS2 propagation and purification was reported previously [17, 25]. Briefly, the ATCC 15597 *E. coli* was used as the host bacteria for MS2. The *E. coli* was amplified in the tryptic soy broth liquid media at 37 °C and shaken at 200 rpm. The MS2 was inoculated into the *E. coli* suspension when the absorbance at 420 nm wavelength reached 0.8. The MS2 incubation lasted for 24 hours at 37 °C with the suspension shaken at 200 rpm. After incubation, the bacteria debris were precipitated by centrifuge at 5000 rpm for 15 minutes, and were further removed by filtering the supernatant with a 0.2 µm Millipore hydrophilic membrane (Bedford, MA). Further purification of the MS2 stock was conducted in a Millipore stirred cell with a Koch 10 kDa MWCO membrane (Wilmington, MA). Each 200 mL MS2 suspension was washed constantly with 1 L of the 1 mM NaHCO₃ solution. The residue of the growth media was washed away, while the MS2 bacteriophage was retained in the stirred cell

by the membrane. The retained MS2 suspension was used as the stock solution for the MS2 inactivation experiment. The MS2 concentration was determined with the plaque forming unit (PFU) method as previously described [26].

2.3 Hydrodynamic Diameter and Electrophoretic Mobility (EPM) Measurement for Particles

The hydrodynamic diameters and the EPMs of MS2, kaolinite, and *Microcystis aeruginosa* were determined with a Malvern NanoZS90 Zetasizer (Southborough, MA) at 25 °C. The concentration of MS2, kaolinite, and *Microcystis aeruginosa* in the measurement were 1.0×10^{11} pfu/mL, 100 mg/L, and 1.0×10^5 Cells/mL, respectively. There were 3 replicates in each measurement. The hydrodynamic diameters of MS2, kaolinite, and *Microcystis aeruginosa* were measured at pH=7 in 1 mM NaCl solution. The EPMs were measured at pH from 3.0 to 8.0. The solution pH was adjusted by 1 mol/L NaOH and HCl. The EPMs were also determined in ionic strength from 2 mM to 200 mM for NaCl and CaCl₂ solutions at pH=7.0.

2.4 MS2 Adsorption onto Kaolinite and *Microcystis aeruginosa*

100 mg/L kaolinite (or 10^5 Cells/mL *Microcystis aeruginosa*) was prepared in NaCl or (CaCl₂ solution) at a certain ionic strength. The solution pH was adjusted to the target value with 1 mol/L NaOH or HCl solution. 0.1 mL MS2 at a concentration of 1.0×10^8 pfu/mL was added to 100 mL of the particle suspension. The mixture was shaken at 200 rpm at 25 °C for 24 hours. The sample was then centrifuged at 2000 g for 30 minutes to separate the suspended and the particle-associated MS2. The MS2 in the supernatant was quantified with the PFU method [27]. A control experiment in the absence of suspended particles was performed in DI water. Three replicates were conducted for each experiment.

2.5 MS2 Inactivation by UV Irradiation

The UV collimated beam apparatus (CBA) with only significant UV emission at 253.7 nm was constructed as recommended by the USEPA [28]. 20 mL of sample in a quartz dish was gently stirred and exposed to the UV irradiation. Prior to each experiment, the CBA was stabilized for 30 minutes to obtain a stable UV irradiation. Every inactivation experiment was replicated twice. A UV dosage of 40 mJ/cm² was chosen because this is the recommended UV dosage in water treatment [29]. The actual UV dosage was determined with the method described previously [30]. Briefly, the average germicidal fluence rate E'_{avg} (UV intensity) in the water was calculated as the product of the radiometer reading at the center of the dish at a vertical position (E_0), the ratio of the average of the incident irradiance over the area of the petri dish to the irradiance at the center of the dish ($P_f = 0.96$), the reflection factor ($R_f = 0.975$), the water absorption factor (W_f), and the divergent factor (D_f). W_f is a water factor, which accounts for the decrease in irradiance arising from absorption as the beam passed through the water, and it is defined as:

$$W_f = \frac{1 - 10^{-al}}{al \ln(10)}$$

where a is the absorbance for a 1 cm path length (cm⁻¹), and l is the vertical path length (cm) of the water in the petri dish. D_f is the divergence factor because the beam is not perfectly collimated and diverges significantly:

$$D_f = \frac{L}{l + L}$$

L is the distance from the UV lamp to the surface of the cell suspension. ($E'_{avg} \times t$) is a constant.

A control experiment to determine MS2 desorption from particles was conducted in the absence of UV irradiation. After adsorption, a sample was taken from the suspension solution and then was injected into elution solution to elute the adsorbed MS2 by continuous shaking with vortexing oscillator. The elution solution consisted

of 8.5 g NaCl and 1.0 g tryptone dissolved in 1000 mL sterile ultrapure water, and the solution pH was adjusted to 7 [31]. The protein-rich eluent disrupts electrostatic bonds between the virus and particle and detaches adsorbed viruses from particle surfaces. MS2 inactivation was calculated based on the infectivity of MS2 present in the solution after elution, including both the unabsorbed MS2 and the MS2 desorbed from particles. The MS2 inactivation in the presence and the absence of particles was compared. Duplicate experiments were conducted for each condition.

2.6 The Extended DLVO (XDLVO) Interaction Energy Profiles

MS2 aggregation and adsorption onto suspended particles were interpreted with the XDLVO theory regarding the energy of van der Waals force (Φ_{vdW}), electrostatic force (Φ_{dl}) and the Lewis acid-base force (Φ_{AB}), as functions of the separation distance h (nm).

$$\Phi_{XDLVO}(h) = \Phi_{vdW}(h) + \Phi_{dl}(h) + \Phi_{AB}(h)$$

Since the hydrodynamic diameters of kaolinite, *Microcystis aeruginosa*, and MS2 are measured to be 1-10 μm , 3 μm , and 26 nm, respectively, kaolinite and *Microcystis aeruginosa* were considered as plane surfaces in the MS2 adsorption. The MS2-particles Φ_{vdW} was calculated with the following expression [32]:

$$\Phi_{vdW}(h) = -\frac{A_{123}r_p}{6h} \left[1 + \left(\frac{14h}{\lambda} \right) \right]^{-1}$$

where $A_{MS2-H_2O-kaolinite}$ is 7.50×10^{-21} J and $A_{MS2-H_2O-Fachb}$ is 2.0×10^{-21} J. r_p (13 nm) is the MS2 radius. λ (10^{-7} m) is the characteristic wavelength of the sphere-plate interactions. The $\Phi_{dl}(h)$ was calculated as [33]:

$$\Phi_{dl}(h) = \pi \varepsilon_r \varepsilon_0 r_p \left[2\Psi_p \Psi_s \ln \left(\frac{1 + e^{-\kappa h}}{1 - e^{-\kappa h}} \right) + (\Psi_p^2 + \Psi_s^2) \ln(1 - e^{-2\kappa h}) \right]$$

The $\Phi_{AB}(h)$ was calculated as [34]:

$$\Phi_{AB}(h) = 2\pi r_p \lambda_{AB} \Phi_{AB(h=h_0)} \exp\left[\frac{h_0 - h}{\lambda_{AB}}\right]$$

where λ_{AB} (1 nm) is the water's decay length [35]. $\Phi_{AB(h=h_0)}$ (J/m²) is the Lewis acid-base free energy of interaction between particles as $h=h_0$. For MS2-kaolinite, MS2-*Microcystis aeruginosa*, and MS2-MS2, $\Phi_{AB(h=h_0)}$ is -5.35×10^{-6} J/m², -3.2×10^{-7} J/m², and -2.69×10^{-6} , respectively, with $h_0=0.25$ nm.

The interaction energy between MS2 virions was calculated using a sphere-sphere model [36, 37]:

$$\Phi_{vdW}(h) = -\frac{A_{123}}{12} \left\{ \frac{1}{\xi^2 + \xi + \xi} + \frac{1}{\xi^2 + \xi + \xi + 1} + 2 \ln \left[\frac{\xi^2 + \xi + \xi}{\xi^2 + \xi + \xi + 1} \right] \right\}$$

where

$$\xi = \frac{h}{r_p}$$

$\Phi_{dl}(h)$, $\Phi_{AB}(h)$ were calculated as follows [33, 38]:

$$\Phi_{dl}(h) = \pi \epsilon_r \epsilon_0 \frac{r_p}{2} \left[2 \Psi_p^2 \ln \left(\frac{1 + e^{-\kappa h}}{1 - e^{-\kappa h}} \right) + 2 \Psi_p^2 \ln(1 - e^{-2\kappa h}) \right]$$

$$\Phi_{AB}(h) = \pi \lambda_{AB} r_p \Phi_{AB(h=h_0)} \exp\left[\frac{h_0 - h}{\lambda_{AB}}\right]$$

3. Results and Discussion

3.1 Effect of Particle Concentration on MS2 Inactivation by UV irradiation

As shown in Fig. 1, in 1 mM NaCl solution at pH=7.0, the log₁₀ inactivation of MS2 remained at about 2.5 log₁₀ with the concentration of kaolinite and *Microcystis aeruginosa* varying from 0 to 100 mg/L and 0 to 10⁶ Cells/mL, respectively. The concentration of particles had no significant impact on the inactivation of MS2. Templeton et al. [39] found that the kaolin clay particles did not result in a statistical reduction in log₁₀ inactivation of MS2 at two UV dose (40 and 80 J/m² and pH=5.5).

Our observation is consistent with a previous report that kaolinite and *Microcystis aeruginosa* did not protect MS2 from the UV irradiation at pH=7.0. The UV absorbance by suspended particles became greater with the increasing concentration of particles. To make sure that the UV dose delivered to MS2 was not affected by the elevated particle concentrations [39], the irradiation time was increased proportionally to achieve the same dose (i.e. from 376s for particle-free water to 430s for the 100mg/L kaolinite solution in Fig. 1(A)).

FIGURE 1

3.2 Effect of pH on MS2 Inactivation by UV in the Presence of Particles

As shown in Fig. 2, the MS2 inactivation in particle-free solution increased from 1.7 to 2.5 log₁₀ with the pH changing from 3.0 to 8.0. The higher MS2 inactivation at pH=8.0 can be attributed to the lack of MS2 aggregation. As shown in Fig. 3, at pH=3.0, the MS2 aggregation resulted in a 0.34±0.08 log₁₀ decrease of the suspended MS2 concentration, while the decrease at pH=8.0 was only 0.03 log₁₀. MS2 aggregated at pH=3.0 because this pH is close to the MS2 isoelectric point (IEP) of 3.7 [40]. Similar aggregation of MS2 has been observed with the pH close to IEP previously [41]. Due to the MS2 aggregation at pH=3.0, the MS2 virions at the outer surface of the aggregate protected the virions inside the aggregates from the UV irradiation. At pH=8.0, the repulsive electrostatic forces between MS2 particles kept the MS2 particles mono-dispersed in the suspension [6]. With each individual MS2

particle exposed to the UV irradiation at pH=8.0, a higher MS2 inactivation was observed compared to the aggregates at pH=3.0. In the pH range from 5.0 to 8.0, MS2 inactivation did not change with pH, as shown in Fig. 2, since MS2 particles did not aggregate in this pH range, as shown in Fig. 3. In summary, MS2 aggregation attenuated the UV irradiation for the virions within the aggregates and thus decreased the overall inactivation.

FIGURE 2

The influence of particles on MS2 inactivation was not consistent in the pH from 3.0 to 8.0. At pH=3.0, the presence of either kaolinite or *Microcystis aeruginosa* increased the MS2 inactivation by 0.3 logs compared to the particle-free solution, as shown in Fig. 2. The increase of MS2 inactivation in the presence of particles at pH=3.0 can be attributed to the MS2 adsorption to particles. As shown in Fig. 3, the MS2 adsorption onto the kaolinite decreased the suspended MS2 concentration by 0.7 log₁₀, and 0.5 log₁₀ for the *Microcystis aeruginosa*. Unlike the MS2 aggregates, where inner MS2 in the aggregate were protected by the outer MS2, MS2 adsorbed to the surface of the particles did not get protection against the UV irradiation [39]. Therefore, at pH=3.0, MS2 adsorption onto particles increased MS2 inactivation compared to that in the absence of particles. With the pH higher than 4.0, the adsorption of MS2 onto particles was minimal, as shown in Fig. 3, probably because of the repulsive interaction force between MS2 and the particles, and thus the presence of particles did

not affect the mono-dispersity of MS2 virions [25]. As a result, the MS2 inactivation in the presence and the absence of particles was not significantly different at pH higher than 4.0.

FIGURE 3

The observed MS2 adsorption at different pH values could be elucidated by the XDLVO profile, as shown in Fig. 4. $\Phi_{XDLVO}/K_B T$ was larger with the increasing pH at the same distance. The lowest energy barrier near zero was found at pH=3.0, favoring MS2 aggregation or adsorption and consistent with the observed trend shown in Fig. 3. It is also shown in Fig. 4 that the energy barrier for MS2 adsorption onto kaolinite was greater than the adsorption onto *Microcystis aeruginosa* at the same pH (i.e., $19.1 K_B T$ and $24.4 K_B T$, respectively, at pH=8.0). This difference in energy barrier indicated that MS2 adsorbed onto kaolinite more favorably than onto *Microcystis aeruginosa*. Consistently, $0.1 \log_{10}$ adsorption was observed for kaolinite versus $0.03 \log_{10}$ for *Microcystis aeruginosa* at pH=8.0, as shown in Fig. 3.

FIGURE 4

3.3 Effect of Ionic Strength on the MS2 Inactivation by UV in the Presence of Particles

As shown in Fig. 5 (A), the UV inactivation of MS2 did not change with the NaCl

concentration at pH=7.0, and the MS2 inactivation efficacy remained at about 2.5 log₁₀. The independence of MS2 inactivation of the NaCl concentration can be explained by the absence of MS2 aggregation in NaCl solutions. The stability of MS2 suspension due to steric repulsion of MS2 capsids has been reported previously [7, 24]. Penrod et al. attributed these steric interactions to polypeptides of loops at the capsid surface [42].

FIGURE 5

In contrast to the observation in the NaCl solutions, Ca²⁺ has a significant effect on the destabilization of MS2 virions. Fig. 5 (B) shows that the log₁₀ inactivation of MS2 decreased from 2.8 log₁₀ to 1.2 log₁₀ in the particle-free solution when the ionic strength of the CaCl₂ solution increased from 2 to 200 mM. The decrease of MS2 inactivation in the Ca²⁺ solutions can be attributed to MS2 aggregation. As shown in Fig. 6 (B), virus aggregation in 200 mM ionic strength CaCl₂ resulted in a 0.8 log₁₀ decrease of the suspended MS2 concentration. The enhancement of MS2 aggregation by Ca²⁺ due to the inner sphere complexation with carboxylate function groups on virus capsid has been reported previously [7, 43]. Because of MS2 aggregation in the presence of Ca²⁺, virions on the outer surface of the aggregate would protect the inner viruses from UV irradiation. This protection resulted in the observed decrease of MS2 inactivation by UV.

FIGURE 6

In the presence of the particles (both kaolinite and *Microcystis aeruginosa*), MS2 inactivation was 2.5 log₁₀ even when the concentration of Na⁺ increased to 200 mM (Fig. 5 (A)). The observed independence of MS2 inactivation with the NaCl concentration in the solution containing particles was consistent with the lack of MS2 adsorption to these particles, as shown in Fig. 6 (A). The log₁₀ adsorption of MS2 on particles remained insignificant with the increasing Na⁺ concentration in both the kaolinite and *Microcystis aeruginosa* suspensions.

For the CaCl₂ solutions in the presence of the model particles, the MS2 inactivation decreased by 0.76 log₁₀ when the ionic strength of the CaCl₂ solution increased from 2 to 200 mM (Fig. 5 (B)). The decrease of MS2 inactivation with the increasing CaCl₂ concentration indicates that some MS2 virions were protected from UV irradiation in the presence of particles. It is highly possible that the adsorbed MS2 formed multiple layers on the particles surface, and thus the virions in the inner layer were not exposed to UV irradiation.

FIGURE 7

To understand MS2 adsorption onto particles, the electrophoretic mobility (EPM) of kaolinite and *Microcystis aeruginosa* in different ionic strengths of NaCl and CaCl₂ solutions are shown in Fig. 7. The EPMs of kaolinite and *Microcystis aeruginosa* were significantly less negative in CaCl₂ solutions than in NaCl solutions. For the kaolinite particles, the EPM in the 10 mM ionic strength CaCl₂ solution was even less

negative than in the 200 mM NaCl solutions. The less negative EPM in CaCl₂ solutions favors MS2 adsorption onto the kaolinite particles, compared to NaCl solution, as shown in Fig. 6 (A) and (B). For the *Microcystis aeruginosa*, the less negative EPM in CaCl₂ solutions was also observed but not as pronounced as that for the kaolinite. However, due to the presence of carboxylate groups on the *Microcystis aeruginosa* surface, the previously reported complexation effect of Ca²⁺ [7, 43] enhanced the MS2 adsorption onto *Microcystis aeruginosa*. Therefore, significant MS2 adsorption onto *Microcystis aeruginosa* was also observed, as shown in Fig. 6 (B).

In CaCl₂ solutions with the ionic strength higher than 50 mM, the MS2 inactivation in the particle-free solution was significantly lower than that in the particle-containing solutions, as shown in Fig. 5 (B). Note that the suspended MS2 concentrations in the CaCl₂ solutions were not significantly influenced by the presence of model particles, as shown in Fig. 6 (B), the higher MS2 inactivation in particle-containing solutions indicates that virions adsorbed onto particles were not protected from UV irradiation as well as that in the MS2 aggregate. The different effects of MS2 aggregation and adsorption can be attributed to the size of suspended particles. In the hydrodynamic diameter measurement, the size of kaolinite and *Microcystis aeruginosa* particles were 1-10 µm and 3 µm, respectively, which are orders of magnitude larger than the MS2 diameter of 26 nm. Due to the size of kaolinite and *Microcystis aeruginosa* particles, there were more virions exposed to UV in the case of MS2 adsorption to particles than the MS2 aggregates that occurred in the absence of model particles. As a result,

the presence of model particles enhanced MS2 inactivation by UV in high ionic strength CaCl_2 solutions.

4. Conclusions

In the pH range from 4.0 to 8.0 in 1 mM NaCl solution, or when the concentration of Na^+ changed from 2 to 200 mM in pH=7.0 solution, the lack of MS2 aggregation or adsorption indicated that the MS2 disinfection efficiency by UV is independent of the presence of kaolinite or *Microcystis aeruginosa*. At pH=3.0, the MS2 aggregation in particle-free solution reduced the UV disinfection efficacy. When particles were added to the solutions at pH=3.0, MS2 inactivation decreased by about 0.3 $\log_{10}$ because MS2 virions were more favorable of adsorbing onto the particles surface than forming MS2 aggregates. At pH=7, the divalent ion Ca^{2+} enhanced the MS2 aggregation in the absence of model particles, leading to a reduction in the inactivation efficacy, compared to the NaCl solution at the same ionic strength. In the presence of particles, Ca^{2+} neutralized the particle surface charge or acted as a complexation bridge, promoting MS2 adsorption onto particles more than MS2 aggregation, resulting in an increase in inactivation compared to the condition without model particles.

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Caption of Figures

Fig. 1. The log inactivation of MS2 by UV as a function of the particle concentration in 1 mM NaCl solution. (A) kaolinite. (B) *Microcystis aeruginosa*. The concentration of bacteriophage MS2 is 1.0×10^8 pfu/mL, UV dose is 40 mJ/cm^2 , pH=7.0, T=25°C.

Fig. 2. The log inactivation of MS2 by UV at different pH value. The concentrations of kaolinite, *Microcystis aeruginosa*, and MS2 are 100 mg/L, 1.0×10^5 Cells/mL, and 1.0×10^8 pfu/mL, respectively, UV dose is 40 mJ/cm^2 , T=25°C.

Fig. 3. The log adsorption of MS2 at different pH value. The concentrations of kaolinite, *Microcystis aeruginosa*, and MS2 are 100 mg/L, 1.0×10^5 Cells/mL, and 1.0×10^8 pfu/mL, respectively, T=25°C.

Fig. 4. Calculated XDLVO profiles at different pH values. (A) MS2-kaolinite. (B) MS2-*Microcystis aeruginosa*. The concentrations of kaolinite, *Microcystis aeruginosa*, and MS2 are 100 mg/L, 1.0×10^5 Cells/mL, and 1.0×10^8 pfu/mL, respectively, T=25°C.

Fig. 5. The log inactivation of MS2 by UV disinfection at different ionic strengths. (A) NaCl. (B) CaCl₂. The concentrations of kaolinite, *Microcystis aeruginosa*, and MS2 are 100 mg/L, 1.0×10^5 Cells/mL, and 1.0×10^8 pfu/mL, respectively, contact time is 1 minute, pH=7.0, T=25°C.

Fig. 6. The log adsorption of MS2 at different ionic strengths. (A) NaCl. (B) CaCl₂. The concentrations of kaolinite, *Microcystis aeruginosa*, and MS2 are 100 mg/L, 1.0×10^5 Cells/mL, and 1.0×10^8 pfu/mL, respectively, pH=7.0, T=25°C.

Fig. 7. The electrophoretic mobility of (A) kaolinite and (B) *Microcystis aeruginosa* at different ionic strengths of NaCl (black squares) and CaCl₂ (red circles). The concentrations of kaolinite and *Microcystis aeruginosa* are 100 mg/L and 1.0×10^5 Cells/mL, respectively, pH=7.0, T=25°C.

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